TO SEEP OR NOT TO SEEP?
SOME CONSIDERATIONS REGARDING WATER INFILTRATION IN VOLCANIC LAKES

Micol Todesco (1), Dmitri Rouwet (1), Massimo Nespoli (1,2), Raul A. Mora-Amador (3)

(1) INGV - Sezione di Bologna, via D. Creti 12 40128 Bologna, Italy
e-mail: micol.todesco@bo.ingv.it
(2) Università di Bologna, Bologna, Italy
(3) Red Sismológica Nacional, Universidad de Costa Rica, San José, Costa Rica

ABSTRACT

Volcanic lakes occasionally form as rainwater fills inactive craters. Their existence and survival requires a delicate balance between meteoric recharge, evaporation, and water loss by infiltration within the volcanic edifice, commonly referred to as seepage. Temperature and composition of lake waters often testify to the presence of a deep-seated, volcanic component that may participate to a varying extent in the lake's evolution. In this work, we investigate the interaction between hot volcanic gases, provided by a magmatic source at depth, and the shallow lake water, fed by meteoric recharge. We focus on the conceptual model developed for Poás Volcano (Costa Rica), where a shallow magma intrusion drives the hydrothermal activity underneath and around a crater lake. The computational domain describes the upper portion of the volcanic edifice where the crater lake is located. Along its base, the domain connects to a reservoir of hot, pressurized water vapor, representing the contribution of deep-seated volcanic fluids. Numerical simulations assess the role of relevant system properties, including the conditions of the hydrothermal reservoir, the water level in the lake, and rock permeability. Preliminary results suggest that very shallow features can be responsible for the dynamics around the lake and ultimately control its evolution.

INTRODUCTION

Crater lakes on active volcanoes are very special geological features. Their evolution through time reflects not only changes in the hydrological cycle, but also changes in the magmatic-hydrothermal system that feeds the lake both heat and fluids. Volcanic surveillance programs commonly highlight significant changes in lake water level, temperature, and composition (Rowe et al., 1992; Rouwet et al., 2004; Terada et al., 2012). The interpretation of these changes, however, is not straightforward, and the information provided by the evolution of the lake is difficult to exploit completely. The presence of shallow liquid water may act as a buffer and hinder signs arising from the magmatic system at depth. Some relevant quantities, such as water loss (or seepage) through lake boundaries, are difficult to measure directly. In this work, we focus on the interactions between the hot rising volcanic fluids and the lake waters. We consider the upper portion of a volcanic edifice hosting a lake and perform numerical simulation of heat and fluid propagation from a shallow, pressurized hydrothermal reservoir through an unsaturated volcanic edifice, toward the surface. We define the computational domain and boundary conditions based on data available for Poás Volcano, Costa Rica. Our simulations, however, are not aimed at reproducing any specific feature of this particular volcanic lake, but rather at investigating some general aspects related to the interaction between hydrothermal fluids and volcanic lakes.

THE POÁS VOLCANIC LAKE

Poás Volcano belongs to the Central Volcanic Cordillera of Costa Rica and is one of its most active volcanoes. The summit of this large basaltic-andesite stratovolcano hosts three cones and two lakes. The active crater, 800 m wide and 2300 m asl, contains an active hydrothermal system, a hot, acidic crater lake, Laguna Caliente, 300 m in diameter, and a dome that extruded during the last phreato-magmatic event in 1953–1955. Volcanic activity has been ongoing almost continuously during the last two centuries, involving hydrothermal and fumarolic

activity, phreatic explosions (1980–1990s, 2006-present) and phreato-magmatic eruptions (1834, 1910, 1953-55) (Casertano et al., 1983; Rowe et al., 1992; 1995; Martínez et al., 2000; Mora-Amador, 2010). Geophysical surveys highlighted the presence of a very shallow magma reservoir, which provides both heat and fluids to the system. Shallower and cooler magmatic intrusions are inferred to exist above the magma reservoir (Brown et al., 1989; Rymer et al., 2000; 2009; Fournier et al., 2004). Fumaroles may form (or disappear) on the dome, and their temperatures range from less than 100 to about 1000°C during periods of volcanic unrest (Brown et al., 1989; Vaselli et al., 2003). Hot, acidic springs are located along the northwest flank of the volcano, at ~ 3 km from the active crater. These springs formed along a (lava-lahar) stratigraphic contact that represents a preferential hydraulic pathway driving the hot hydrothermal brines from the crater region down on the volcano's flank (Rowe et al., 1992; 1995). The Laguna Caliente lake was formed on the active crater. The water level has been highly variable, from 50 m to 0 m (Rowe et al., 1992). Steady evaporation dominates during periods of high lake water temperature (as high as 80°C), which are directly related to enhanced magmatic activity at Poás. The decline of the water level, and occasionally the complete lake's desiccation, preceded the onset of phreato-magmatic and magmatic eruptions in 1910 and 1953. During quiescent periods, lower water temperatures (as low as 20°C) are associated with higher lake levels. Water level and properties (temperature, composition) also depend on meteoric recharge. Precipitation in the summit area at Poás ranges from 120 mm/month in the dry season (December-April) to as much as 420 mm/month (May-November). Considering a catchment area corresponding to the crater surface (7.1×10^5 m^2), these values correspond to an average meteoric recharge ranging from 34 to 114 kg/s.

NUMERICAL MODELING

In this work, we focus on the interplay between the lake water infiltrating through the volcanic edifice and the hydrothermal system. In particular, we consider a quiet period, when neither the water level nor the lake temperature is expected to change significantly, as occurred from 1995 to 2005 (Rymer et al., 2009). We describe a small region of the volcanic edifice, 250 m deep and 1000 m wide, located between the shallow hydrothermal reservoir formed above the magma body and the crater lake (Figure 1). We consider a simple 2D, axisymmetric domain, composed by 2288 elements with a constant thickness of 5 m and a radial dimension ranging from 5 to 100 m. Numerical simulations are performed with TOUGH2/EOS3, to describe the propagation of hot volcanic vapor and of lake water into an initially unsaturated volcanic edifice.
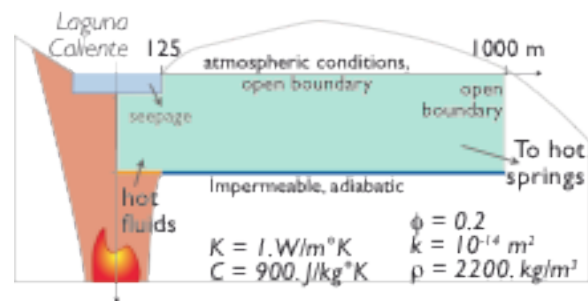

Figure 1. Computational domain, rock properties, and boundary conditions applied for the numerical simulation of the Poás hydrothermal system.

The presence of the lake is simulated as a boundary condition, with fixed pressure, temperature, and water saturation prescribed along the lake bottom and vertical border: pore pressure is fixed at the hydrostatic value for the corresponding lake depth; the pores are fully saturated with water whose temperature is set at 25°C. Lake-water evaporation at this temperature (Fournier et al., 2009) is about one order of magnitude smaller than the average meteoric recharge, and therefore we neglect this effect. With the imposition of a steady water level and a constant water temperature, we assume that the meteoric precipitation and the inflow of hydrothermal condensates perfectly balance the water loss through the lake boundaries. At this time, we also assume that precipitation mostly feeds the lake, while we consider the slopes of the volcano steep enough to prevent infiltration elsewhere in the domain.
In this simple model, the hydrothermal circulation is fed by a hot and pressurized, dry-gas reservoir, located at shallow depth right below the lake. Where not otherwise specified, the reservoir is set at 350°C and 2.4 MPa. These

values were selected considering the temperature proposed for the magmatic intrusion (Rowe et al., 1995) and the hydrostatic pressure at that depth. The outer portion of the bottom boundary is closed to heat and fluid flow, and represents the presence of an impervious layer that drives fluids outward to feed the springs along the volcano slopes. The lateral boundary is open, unsaturated, and at fixed atmospheric conditions (0.1MPa and 15°C). At the beginning of the simulation, the entire volcanic edifice is considered fully saturated by air at atmospheric conditions. Where not otherwise specified, the physical properties of the rock are homogeneous and set as shown in Figure 1. Based on this simple conceptual model, we investigated the role of selected system parameters, such as the conditions of the hydrothermal reservoir feeding the system, permeability of the volcanic rock, and lake water level.

THE REFERENCE CASE

At the beginning of the simulation, the lake water begins to infiltrate into the volcanic rock, while the hot, pressurized vapor in the hydrothermal reservoir propagates upward, heating the lower portion of the domain. A small fraction of this vapor condenses, forming a small rim of warm, liquid water around the edges of the rising plume. After 3 years of simulation, the cold water seeping downward and the hot, ascending fluids merge at a depth of about 150 m (Figure 2a). From this time on, the downward motion of the water is diverted by the uprising fluids. The cold lake water and the hydrothermal condensate, reach the bottom of the domain at some 250 m from the symmetry axis (Figure 2b). As the simulation continues, the interface between the cold water and the hot rising vapor keeps changing. After 40 years, the hot plume reaches the bottom of the lake (Figure 2c) and starts to increase both the temperature and pore pressure along its base. As a consequence, the water seepage through the bottom of the lake is progressively hindered and, at the end of the simulation, the water leaves the lake mostly through its vertical border (Figure 2d). The water that accumulates along the impervious base of the domain is slightly heated (50°C) and tends to propagate outward. At the end of the simulation (100 yr), it has reached as far as 900 m from the symmetry axis (not shown). The entire simulation is shown here for completeness, but when the hot plume reaches the bottom of the lake, water vapor is expected to enter the lake, altering its level and temperature. As a result, our assumption of steady lake conditions would not be realistic anymore. Numerical results allow us to quantify the seepage under the simulated conditions.
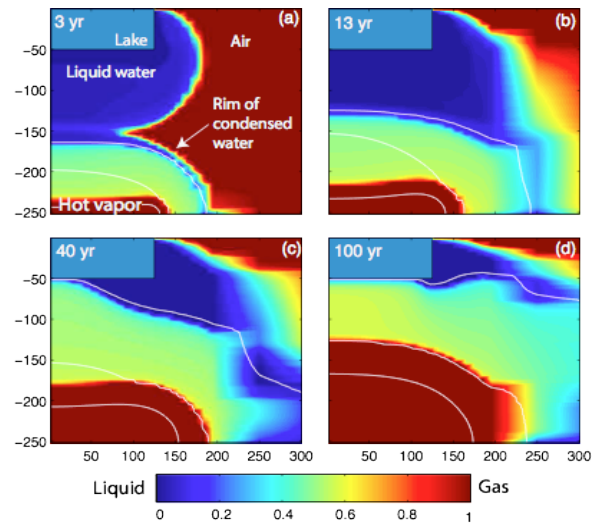

Figure 2. Volumetric gas fraction in the lake region, at different times (reference simulation). The three white contours correspond to temperature of 100°, 200°, and 300°C.

Figure 3 shows the amount of water that leaves the lake through the bottom and the vertical borders, as a function of time. The overall trend is negative, indicating that water loss tends to diminish through time. Water seepage is driven by gravity and by the pressure gradient across the lake boundaries. The liquid water of the lake is denser than the air that initially fills the rock pores, and its hydrostatic pressure is everywhere greater than the atmospheric value that is initially set within the unsaturated volcanic edifice. As liquid water begins to infiltrate, both the density contrast and the pressure gradient across the lake boundaries tend to vanish, and the seepage correspondingly declines through time. This trend, however, is not linear, and the initial quick drop of the seepage rate is followed by a more gentle, steady decline that lasts to the end of the simulation. This abrupt change occurs after about 7 years, when the rock around the lake becomes entirely saturated by liquid water or by a two-phase mixture of hot vapor and water, and the pressure profile around the lake

becomes more stable. The vertical seepage (green in Fig. 3) is initially larger than the horizontal component, but it undergoes a faster decline, and eventually vanishes, as the rising fluids counteract the hydrostatic pressure along the bottom of the lake. After 4 years of simulation, the seepage becomes dominated by the horizontal component, which maintains a rather constant value over time. Figure 3 also shows the time at which the total amount of water lost by seepage equals the amount of water initially present within the lake (cyan dot). Under the conditions considered here, and in absence of meteoric recharge, the lake would drain completely in 12 years. Given that the yearly average precipitation is higher than the simulated seepage rate, the meteoric recharge would easily counteract the effects of seepage in this case.
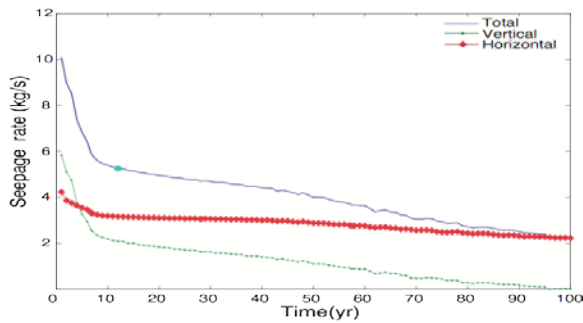

Figure 3. Rate of seepage through the lake bottom (green line) and vertical wall (red line). The cyan dot on the total seepage curve (blue line) indicates the time at which the seepage would completely drain the lake, in absence of meteoric recharge.

THE HYDROTHERMAL RESERVOIR

The evolution of seepage is influenced by the conditions assigned to the reservoir of volcanic fluids. To investigate the effect of these conditions we performed two sets of simulations: the first one explores different reservoir temperatures (from 50° to 300°C) at a fixed pressure (2.4 MPa), whereas the second set describes the role of different reservoir pressures (from 0.7 to 2.8 MPa) at fixed temperature (350°C). All simulations were run for 100 years, and results are compared with those achieved in the reference case.

The reservoir conditions control the phase of the fluid entering the system. For a reservoir pressure of 2.4 MPa, as in the reference case, the saturation temperature is about 220°C. Simulations run with reservoir temperatures up to 200°C therefore describe a system fed by hot liquid water that saturates the domain up to a depth of 150 m, and then mostly propagates outwards, slightly affecting the temperature near the surface (Figure 4a). Higher reservoir temperatures cause the inflow of hot vapor that rises toward the surface and heats the system more efficiently (Figure 4b,c).
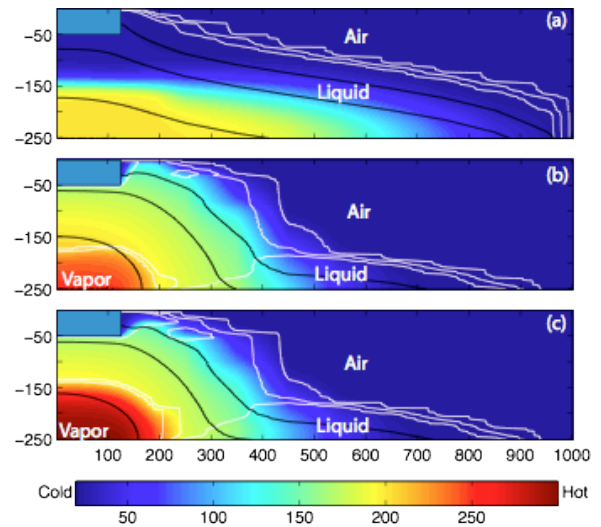

Figure 4. Distribution of temperature (color), pressure (black contours) and volumetric gas fraction (white contours) after 100 yr of simulation. Reservoir temperatures of 200°C (a), 250°C (b) and 300°C (c). Pressure values: 0.4, 0.8, 1.6, 2.4 MPa; gas fraction: 0.3, 0.6, 0.9.

Note that near-surface temperatures do not necessarily reflect the reservoir temperature, since the isotherms around the lake are controlled by complex, small-scale patterns of circulation (Figure 4b,c).

The pressure assigned to the hydrothermal reservoir also affects system evolution. As we set the reservoir temperature at 350°C, the reservoir fluid is always steam at all the considered reservoir pressures. However, values below 2 MPa do not sustain the ascent of the reservoir fluid against the downward motion of the lake water (Figure 5a). In this case, the presence of the hydrothermal reservoir does not

affect the lake, while the lake water saturates the domain and eventually enters the reservoir. Above this pressure value, the ascent of hydrothermal fluids, and the associated heating, are granted (Figure 5b,c). Higher pressures favor a faster evolution: the steam from the reservoir reaches the bottom of the lake in 95 years, when the reservoir pressure is 2.1 MPa, only 23 years after the maximum pressure is assigned. Pressure and temperature of the reservoir influence the seepage process (Figure 6).
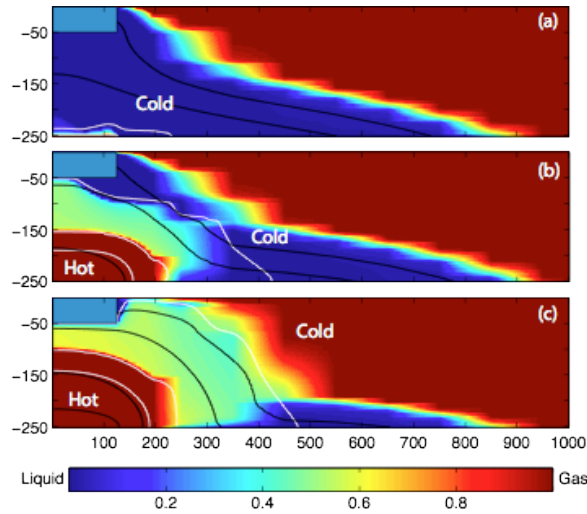

Figure 5. Distribution of gas fraction (color), pressure (black) and temperature (white) after 100 yr of simulation for reservoir pressures of 1.4 MPa (a), 2.1 MPa (b) and 2.8 MPa (c). Pressure contours:0.4, 0.8, 1.6, 2.4 MPa; temperature contours: 100°, 200°, 300°C.

While the general pattern is maintained, with a quick drop in seepage rate followed by a more gentle decline, the absolute values and the details of its temporal evolution depend on the reservoir conditions.

Differences associated with the reservoir temperature increase with time, and become relevant only after a few tens of years (Figure 6a). Note that the effect of reservoir temperature depends on the phase of the fluid within the reservoir: when the source discharges liquid water, the long-term seepage tends to a steady value, maintained throughout the simulation, that is slightly higher for lower reservoir temperature. On the other hand, if the source at depth discharges water vapor, the seepage keeps declining through time, and the reservoir temperature has the opposite effect, with higher temperatures corresponding to higher seepage rates.

Reservoir pressure affects both the initial drop in seepage rate, and its long-term value (Figure 6b). Low reservoir pressures correspond to a small initial decline and to higher and rather constant long-term seepage rates. When the reservoir pressure exceeds 2 MPa, the ascent of hot vapor effectively counteracts the downward motion of liquid water (Figure 5c). Higher reservoir pressures correspond to larger initial drop, and to an overall declining trend throughout the simulation.
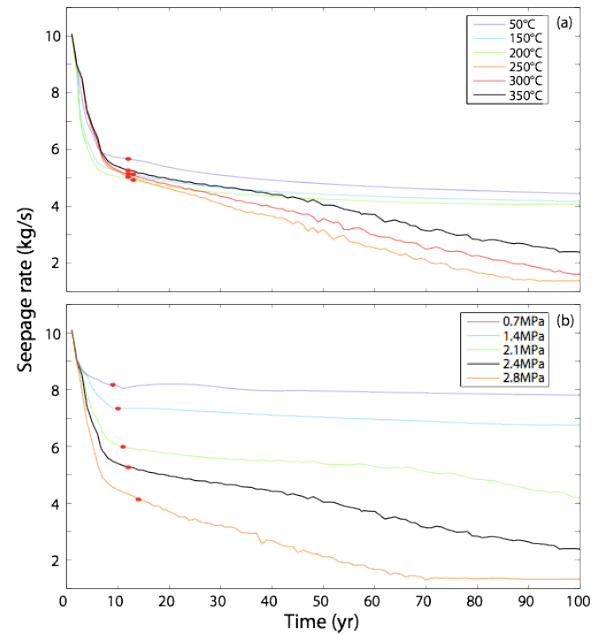

Figure 6. Total seepage rate through time at different reservoir temperatures (a) and pressures (b). The black line refers to the reference simulation. Red dots indicate the time at which the seepage would drain the lake in absence of meteoric recharge.

THE WATER LAKE LEVEL

In all our simulations, the lake has been considered a steady boundary condition. In reality, we know that there are periods during which the lake level changes significantly, modifying the pressure distribution along the lake boundaries. To assess the importance of such a change, we performed a further set of simulations, changing the lake level from 50 to 10 m. As in previous cases, we assume that the

assigned water level is maintained by meteoric recharge and does not change during the simulation. Higher water levels imply a higher hydrostatic pressure at the bottom of the lake and a larger portion of the vertical wall being fully saturated with liquid water. Initially, these differences do not affect the evolution of the system. The interaction of lake waters with the hot, rising vapor takes place in a similar way, and the overall temperature distribution is comparable, whatever the lake thickness is (Figure 7a,b). However, the conditions set along the vertical boundary of the lake affect the amount of water that permeates the surrounding region, and modify the local pattern of circulation. Over the long term, this slightly modifies both the phase distribution and the system temperature (Figure 7c,d).
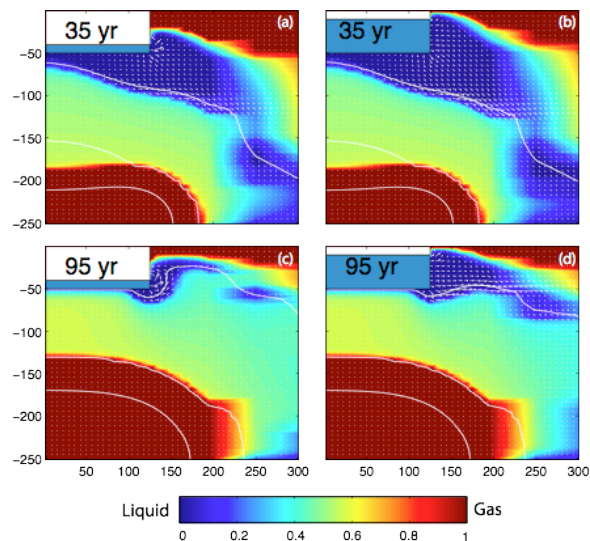

Figure 7. Volumetric gas fraction at different times for a lake level of 10 (a,c) and 40 m (b,d). The three white contours correspond to temperature (100°, 200°, and 300°C). White arrows show the liquid flow pattern.

When the lake level is only 10 m, a large portion of the vertical boundary of the lake is unsaturated and at atmospheric pressure. Under these conditions, the fluids within the volcanic edifice can enter the lake: when the hot vapor reaches the bottom of the lake, pushing the liquid water upwards, some fraction of it flows back into the lake, as shown in Figure 7c.

The different lake levels also affect the total seepage from the lake. While the vertical outflow of water through the bottom of the lake does not change significantly with respect to the reference case (green line, Figure 3), the horizontal seepage is affected by the water level, being reduced from an average value of ~ 3 kg/s, for the maximum lake depth (50 m) to about 1 kg/s, when lake level is only 10 m. As a result, the total seepage changes with lake level, as shown in Figure 8. Lower water levels correspond to lower seepage rates, at any time.

ROCK PERMEABILITY

The interaction between hydrothermal fluids and lake waters also depends on the hydraulic properties of the shallow volcanic rocks.
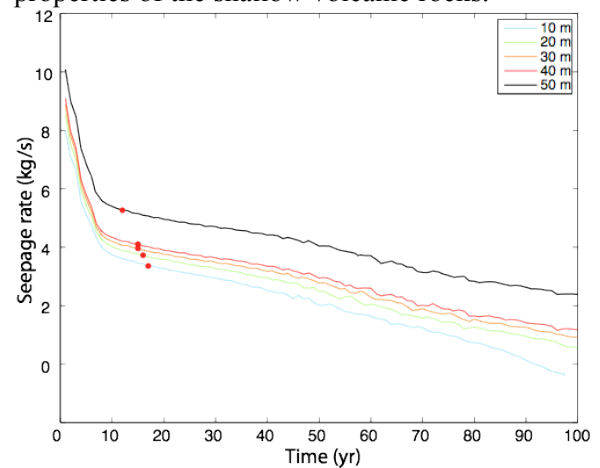

Figure 8. Total seepage rate through time for different water levels. The black line refers to the reference simulation. Red dots indicate the time at which the seepage would drain the lake in absence of meteoric recharge.

Permeability, in particular, affects the rate at which the system conditions evolve through time. Simulations performed with different permeability values (10^{-12} to 10^{-16} m^2) confirm that lower permeabilities cause slower evolution, with similar distribution of temperature and fluid phases achieved at later times in less permeable systems.

The seepage rate also changes, with its order of magnitude increasing with the order of magnitude for permeability. The maximum seepage rates, at the beginning of each simulation, range from 500 to less than 0.4 kg/s

over the considered permeability range. The temporal evolution of the seepage also changes with permeability: a permeable system allows for a quick ascent of hot vapor, which in turn leads to a faster decline of the seepage rate. Less permeable systems are characterized by lower but rather constant seepage rates, which are maintained with small changes to the end of the simulation. All these considerations hold for homogeneous systems. However, active crater lakes are often hosted in stratovolcanoes, where heterogeneous rock properties can be expected. Here we focus on the permeability of the lake boundaries. The permeability of the lake borders controls the amount of liquid water that permeates through the volcanic edifice and the interaction with hydrothermal fluids. Figure 9 and 10 show the phase distribution achieved imposing a very low permeability (10^{-21} m^2) to either the vertical wall of the lake (a), the lake bottom (b), or both (c).
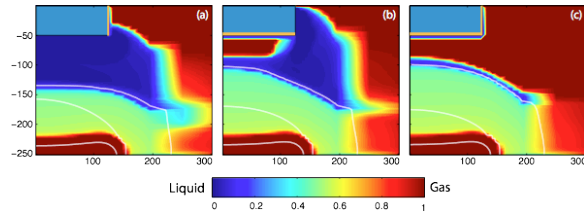

Figure 9.   Volumetric gas fraction after 10 years with low permeability (10^{-21} m^2, yellow line) assigned to the lake vertical wall (a), bottom (b) or both (c). The white contours correspond to temperature of 100°, 200°, and 300°C.

When only the lake bottom is permeable (Fig. 9a), the seepage clearly hinders the ascent of hydrothermal vapor. Where the water infiltration only takes place through the vertical wall, or is totally prevented, near surface-heating is more efficient (Fig. 9b,c). After 100 yr of simulation, the overall system conditions are similar, although not identical (Figure 10). When the lake bottom is permeable, the pressure and temperature underneath the lake are slightly lower than in the other cases, and the gas fraction is correspondingly higher (Fig. 10a).
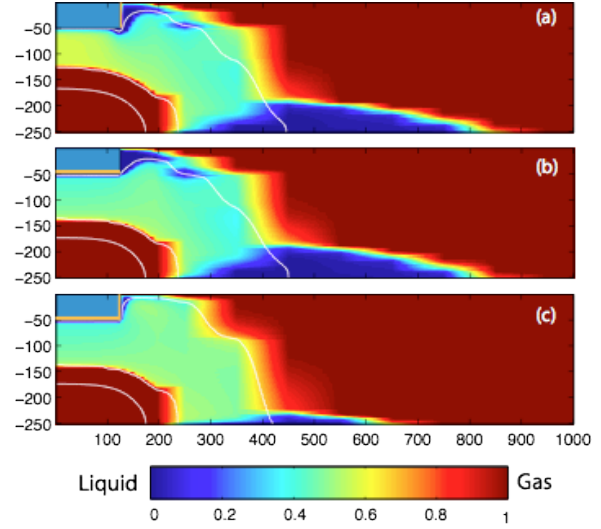

Figure 10. Volumetric gas fraction after 100 years with low permeability (10^{-21} m^2, yellow line) assigned to the lake bottom (a), wall (b) or both (c). The white contours correspond to 100°, 200°, and 300°C.

When any of the lake boundaries is permeable, a larger amount of liquid water permeates the region surrounding the lake, and eventually accumulates along the bottom boundary (Figure 10a,b). Hydrothermal condensate also accumulates along the bottom boundary, so that some liquid water is present along the bottom boundary even when the lake is completely sealed (Fig. 10c). Hydrothermal-vapor condensation takes place in all simulations, but its relative proportion changes, depending on how much water can permeate the system.
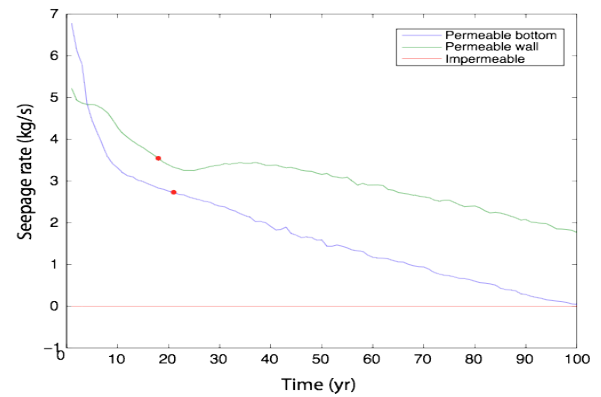

Figure 11. Total seepage rate through time for different permeabilities of the lake boundaries. Red dots indicate the time at which the seepage would drain the lake in absence of meteoric recharge.

The permeability of lake borders also affects the seepage rate (Figure 11). In particular, if only the bottom of the lake is permeable, the seepage rate undergoes the largest variation, and eventually vanishes, hindered by the ascent of the hydrothermal fluids. The seepage through the vertical wall of the lake is affected to a lesser extent by the rising vapor, and turns out to be more effective in draining the lake water.

CONCLUSIONS

We focused on the interaction between a crater lake and the hydrothermal circulation. Numerical simulations were carried out to estimate the infiltration of lake waters (or seepage) at Poás Volcano, under the assumption of steady lake conditions. Our results show that the conditions of the hydrothermal reservoir, the lake water level, and rock permeability may all affect system evolution and the corresponding seepage rate. The infiltration of lake water is effectively hindered by the presence of an active hydrothermal reservoir. Long-term seepage is reduced or totally hindered when the reservoir discharges hot vapor at high pressure. Its ascent effectively reduces the vertical infiltration, limiting the water seepage through the bottom of the lake. Conversely, the horizontal flow through the vertical border of the lake is never completely hindered by the rising fluids. For this reason, the total seepage, and its temporal evolution, are sensitive to conditions set along the vertical boundary of the lake, namely to its water saturation (lake's water level) and to its permeability. Shallow heating and fumarolic activity only develop when water seepage is limited, i.e., when reservoir pressure is high, the water level in the lake is low, or the permeability around the lake is limited. When seepage occurs, liquid water can accumulate along impervious layers, mix with hydrothermal condensates, and eventually propagate to feed hot springs. The hydrothermal component in spring waters is therefore expected to increase when seepage is limited, i.e., when reservoir pressure is high, lake level is low, or the permeability around the lake is reduced. Seepage is difficult to quantify in the field, but is a key parameter in assessing the evolution of the crater lake, and in estimating the volcanic hazard. Further research will be carried out on the feedback between lake conditions and hydrothermal circulation.

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